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THEORETICAL FOUNDATIONS OF GRAVITATIONAL PHYSICS EXPERIMENTS IN SPACE

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FINAL TECHNICAL REPORT

Principles of Equivalence and their Verification by Satellite Experiments

We studied the theoretical implications of proposed satellite tests of the Equivalence Principle, such as STEP and QuickSTEP. These missions have been proposed as possible joint NASA-ESA projects, with the goal of testing the Principle of Equivalence to the level of 10^{-17} , a six-order-of-magnitude improvement over current laboratory experiments. Parts of this work were done by one of us (CMW) as a member of the Theory Panel of the STEP Study Team.

One approach to such a theoretical study is phenomenological, in which one estimates the level of possible violations of the equivalence principle by determining the contributions of various forms of electromagnetic, weak and nuclear interactions to the internal energies of atoms. Post-doctoral fellow M. Reisenberger showed that, within the context of quantum field theory as applied to a class of non-metric couplings to matter, such an approach is valid, despite the renormalization of masses of the constituent particles in the atoms (Reisenberger 1993a). We pointed out (Will 1992) that the contribution of electromagnetic vacuum-polarization (Lamb shift) energies of atomic electrons could be of interesting magnitudes, potentially testable by STEP, yet had not been calculated to date.

We also studied the extent to which STEP could provide a test of short or intermediate range composition dependent forces. Considering the whole Earth as a source of such a force, we showed that, for ranges $\lambda > 7000$ km, a bound could be placed on the coupling strength relative to gravity of such a force of $\alpha < 10^{-14}$, while for ranges as low as 30 km, the bound would still be as low as 10^{-5} . Substantially weaker bounds result from considering the large- l multipoles of the Earth's gravitational field as source. We also estimated the bounds on short-range forces ($1 \text{ m} < \lambda < 30 \text{ km}$) that could be obtained by placing large local masses near the spacecraft. The bounds were only a few orders of magnitude better than current laboratory experiments (which are expected to improve substantially in the near future).

Reisenberger completed a thorough study of the theoretical implications of equivalence principle tests (Reisenberger, 1993b). Within the context of Lagrangian field theories, he studied the extent to which a requirement that test bodies follow geodesics of a metric implies universal, or metric coupling of all gravitational fields to the matter fields (Schiff's

conjecture). He found that, while a class of non-metric couplings could be found that satisfied the geodesic requirement, formally contradicting Schiff's conjecture, they generally corresponded to physically unreasonable theories.

Relic Gravitational Waves and COBE

The quantum-mechanical generation of cosmological perturbations may have observational consequences in the angular variations of the cosmic microwave background radiation as detected by the Cosmic Background Explorer (COBE) satellite. In an expanding universe, there may be a parametric amplification of quantized cosmological perturbations by the variable background cosmological gravitational field that leaves the perturbations in a "squeezed state" analogous to those of nonlinear quantum optics. Grishchuk (1993a) showed that the power spectra of the resulting perturbations are modulated, and the resulting angular distribution of the temperature fluctuations of the cosmic microwave background is very specific. The variance of the temperature fluctuations caused by these gravitational perturbations is rotationally symmetric with respect to an axis, and reflectionally symmetric with respect to the plane orthogonal to the axis. This angular pattern can, in principle, be revealed by COBE-type observations.

He also showed (Grishchuk 1993b) that rotational perturbations could be generated in the early universe by quantum mechanical effects, and that they could contribute to the measured anisotropy of the cosmic background radiation. He further argued (Grishchuk 1994), using a simple scalar-field model, that cosmological perturbations of quantum-mechanical origin should be dominated at the epoch of generation of the microwave background by gravitational waves, rather than by density perturbations.

Bounds on post-Newtonian Parameters

Discussion of future space experiments to test gravity relies upon knowledge of the current experimental bounds on the parameters of post-Newtonian gravity and the theoretical significance of those bounds. In collaboration with K. Nordtvedt, we began a thorough review of the current observational bounds on the standard 10 parameters of the Parametrized post-Newtonian (PPN) framework. We also plan to study the desirability of adding selected new PPN parameters related to interesting and potentially testable effects.

Effects of Spin on the Gravitational Waves from Inspiralling Compact Binaries, and Space-based Gravitational Observatories

Orbiting laser-interferometric gravitational-wave detectors such as the proposed LAGOS or SAGITTARIUS/LISA missions could detect gravitational waves from the inspiral of stars or black holes into supermassive black holes at the centers of galaxies. Since such black holes are expected to be spinning, the effects of spin-orbit and spin-spin coupling on the inspiral orbits and the gravitational waveforms could be important. We derived the

spin-orbit and spin-spin contributions to the gravitational waveform and to the energy, angular momentum and linear momentum flux from inspiralling binaries (Kidder, *et al.* 1993; Kidder 1994). There are three important consequences of such effects: (i) precessions of the spins of the bodies and of the orbital plane, resulting in modulations of the observed gravitational waveform; (ii) direct contributions of spin-induced terms to the waveform; and (iii) contributions of spin to the energy and angular momentum lost to radiation, resulting in modifications of the inspiral rate and of the observed gravitational-wave phase. The consequences of these effects for space-based detectors are currently under study.

References Supported in Part by this Grant

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